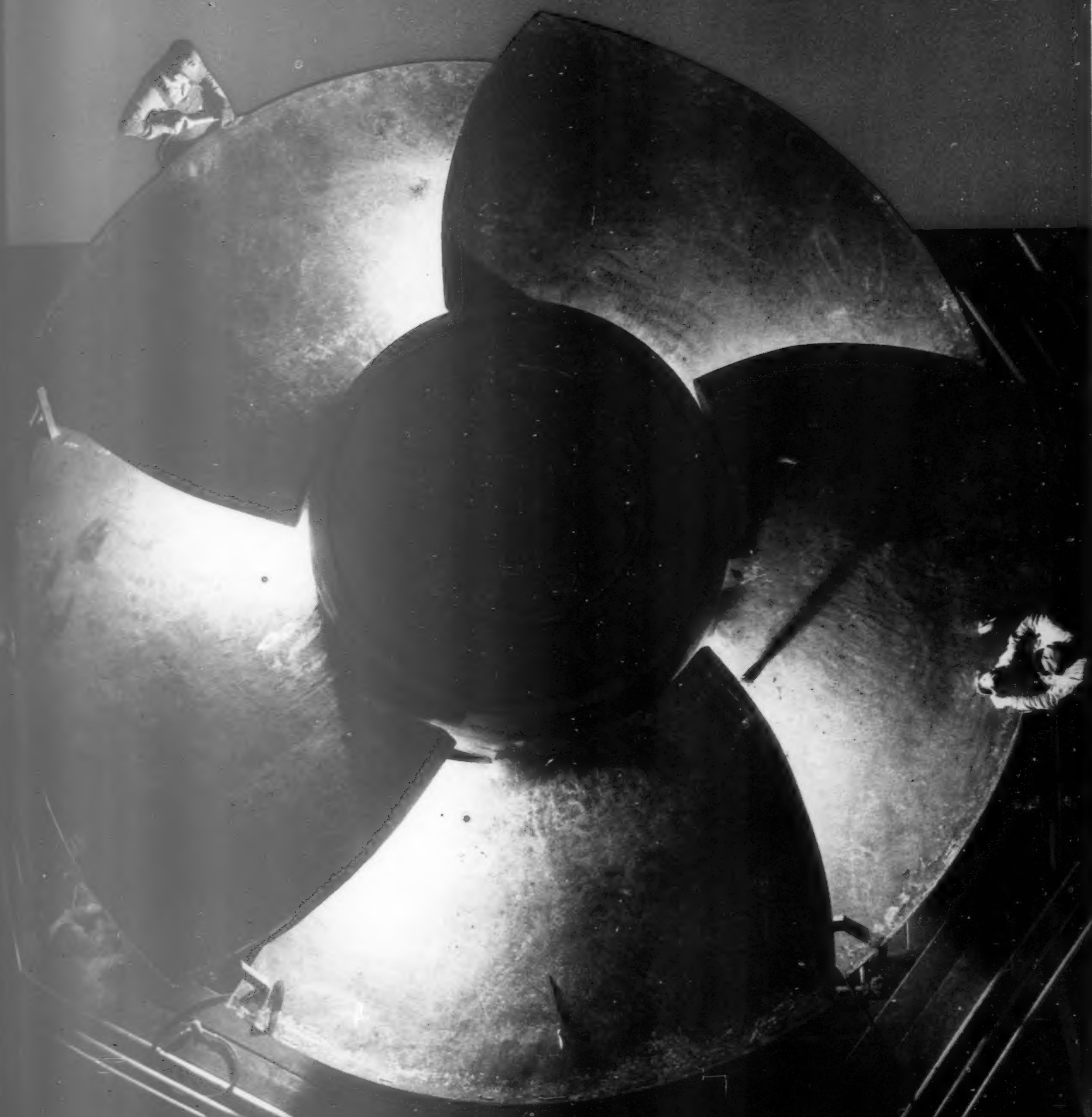
ALLIS-CHALMERS Electrical REVIEW

2ND QUARTER 1952



ALLIS-CHALMERS Electrical REVIEW

THE COVER

STRANGE NEW FLOWER takes shape as workmen begin finishing operations on the Kaplan runner for the 55,000 hp Unit No. 5 at TVA's Pickwick Landing Plant. The completed 24½ ft rotor weighs over 100 tons and is the largest runner of its kind in the U.S. This seldom seen view of a turbine runner was taken from 60 feet up.

A-C Staff Photo by M. Durante

Allis-Chalmers
ELECTRICAL REVIEW
Vol. XVII No. 2

Issued quarterly. Subscription rates: U. S., Mexico, and Canada, $2.00 per year; other countries, $3.00; single copies, $1.00 in advance.

CONTENTS

Indexed regularly by Engineering Index, Inc.
Allis-Chalmers ELECTRICAL REVIEW is available to public and institutional libraries on microfilm from University Microfilms, 313 N. First St., Ann Arbor, Mich.

Address Allis-Chalmers Electrical Review, Milwaukee 1, Wisconsin

Printed in U. S. A.

HIGH LINES in Rough Terrain

by F. D. TROXEL
Senior Electrical Engineer
Vern E. Alden Company, Engineers
Chicago, Illinois

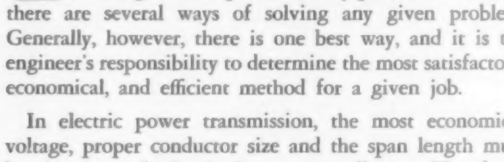
Look over the author's shoulder as he solves a problem in long distance transmission of electric power.

DELIVERING A LARGE block of electric power a considerable distance from the point at which it is generated presents many problems. Usually there are several ways of solving any given problem. Generally, however, there is one best way, and it is the engineer's responsibility to determine the most satisfactory, economical, and efficient method for a given job.

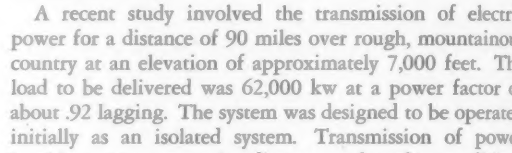
In electric power transmission, the most economical voltage, proper conductor size and the span length must be chosen to obtain the lowest over-all cost. The detail line design must be such as to give reliable operation, bearing in mind the climatic conditions, soil conditions and general locaton of the line. The question of voltage regulation on the whole system and the need for a synchronous condenser must be carefully considered, keeping in mind the kva load and power factor of the generator. Thus, in a thorough study of such a problem, one touches upon many interesting aspects of electrical equipment and system design.

A recent study involved the transmission of electric power for a distance of 90 miles over rough, mountainous country at an elevation of approximately 7,000 feet. The load to be delivered was 62,000 kw at a power factor of about .92 lagging. The system was designed to be operated initially as an isolated system. Transmission of power in this amount over the distance and under conditions indicated presented several considerations requiring careful engineering.

The load which is imposed on a generator in such a system tends to be at a low power factor and low power factor loads increase the kva and ampere loading on the generator. At power factors below .95 lagging, the heavy



TOTAL TRANSMISSION COST at various voltages. 110 kv cost was about 8 percent more than 138 kv. Latter was selected as the best all-around choice. **(FIGURE 1)**



CONDUCTOR SIZE vs. transmission cost proves 400,000 C.M. copper best choice. Equivalent ACSR conductor was substituted for cost and availability reasons. **(FIGURE 2)**

voltage drops in the transformers and overhead circuits tend to fall beyond the economical and practical operating range. Since high voltage power transmission requires a high power factor, the necessary steps were taken to meet this requirement.

The high, mountainous country indicated a high ground resistance with a greater possibility of trip-outs from lightning. Steps had to be taken to reduce trip-outs to a minimum. High winds and low temperatures were anticipated and were included in the basic design consideration.

Adjoining systems affect choice

The voltage for the transmission of this power was chosen so that the line and substations could be interconnected with adjoining systems in the future, if desired. At the same time, the voltage chosen was such that it resulted in the lowest practical total transmission cost. In the transmission of power at the higher voltages, the investment costs rise as the voltage is increased, while the loss is smaller at the higher voltages. Therefore, for a given set of conditions, an economic balance exists between investment costs and loss costs. Also, for a given set of load conditions and distance of transmission, one conductor size will result in a lower over-all transmission cost than any other conductor size.

In economic studies leading to the selection of one of several possibilities, the most desirable choice is usually considered to be at a point somewhat short of the low point on the curve showing these values. In the following discussion, the choices have been made on this basis.

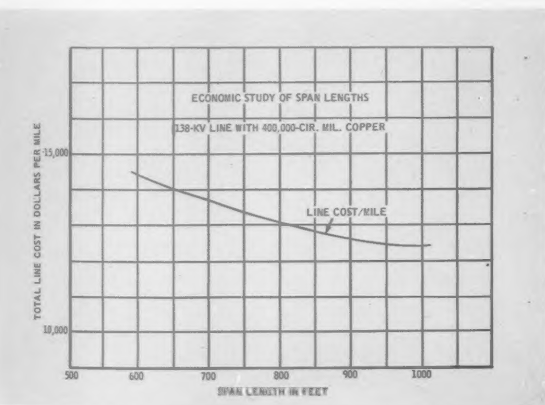
A study of transmission cost made at different voltages from 110 kv to 230 kv resulted in the curve shown in Figure 1. A 138-kv transmission voltage was adopted, since it gives a low transmission cost and it is a widely adopted standard voltage which could be readily connected with other 138-kv lines in the general area.

Various conductor sizes, ranging from 300,000 cir mil to 600,000 cir mil copper, were evaluated to determine which to use. As shown in Figure 2 the 400,000 cir mil copper conductor was considered ideal for the conditions of this study. In the preliminary cost studies of the various conductor sizes it was assumed that copper conductors would be used. While copper conductors offer some advantage from an installation standpoint in a rough terrain, copper was difficult to obtain and cost somewhat more than other materials. Aluminum conductors were chosen to offset the higher cost. A 636,000 ACSR conductor which is equivalent to a 400,000 cir mil copper conductor was selected.

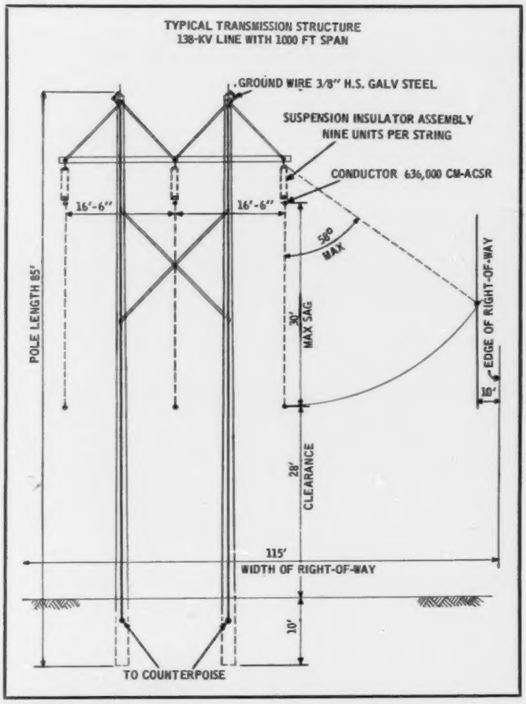
Comparative cost studies were made and revealed that the most economical design for an aluminum conductor line of this voltage is one having about 1,000-foot span lengths as shown in Figure 3. All of the previous discussions are based on this span length. The actual span for each structure, however, was determined after a profile of the right-of-way had been prepared, and advantage was taken of the contour of the country.

The line chosen has a horizontal configuration and the structure is of the H-frame design with wood poles and wood crossarms as shown in Figure 4. Steel structures were considered but their considerably greater cost and the difficulty in obtaining steel under present conditions precluded their use.

Wood pole and crossarm construction has been used on many lines of this voltage in this as well as other sections of the United States. The line was provided with two ground wires and certain precautions were taken to obtain a low ground resistance. The line was designed for one broken conductor; that is, the structures were of sufficient



SPAN LENGTH versus total line cost shows 1000 foot spans (based on 400,000 C.M. copper) most economical. Final length varied according to right-of-way profile. **(FIGURE 3)**



H-FRAME structures of wood were chosen for availability and lower cost. Impulse flashover will pass through air to downlead, not over insulators and along crossarm. **(FIGURE 4)**

strength so that they would withstand the stress imposed if one of the transmission conductors breaks. While the availability of poles in the larger lengths is sometimes a factor in determining the span lengths, it was not a problem in this case.

The poles and 85-foot long tangent structures were of western red cedar. There were, of course, special structures for the longer spans, as dictated by the contour of the country, and at railroad and highway crossings. Special structures were also required at points where the line made a sharp change in direction.

Design minimizes outages

The number of outages per year can be kept low by careful consideration of several basic factors in the design of the line, including:

a. The isokeraunic level of the territory in which the line is located.
b. Pertinent weather data such as maximum and minimum temperatures, maximum wind velocities, sleet formation, and the probable combination of these circumstances.
c. Number of insulators in each string.
d. Spacing between conductors and supporting structures.
e. Midspan spacing from conductors to ground wires.
f. Ground wire location and design.
g. Ground resistance.

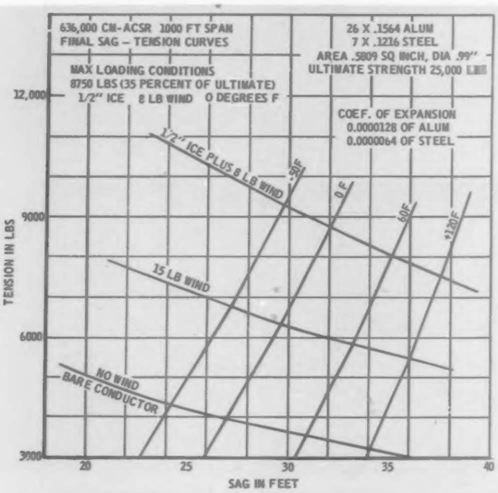
The isokeraunic level of this territory is about 30. The normal maximum wind velocity to be expected ranges from 40 to 60 miles per hour and may be attained many times each year. Occasionally winds attained a velocity of 80 miles per hour. The winds are most frequently out of the southwest, west or northwest, depending upon the particular section of the right-of-way being considered. The minimum temperature to be expected is 50 degrees F below zero, with an expected maximum of about 112 degrees F. Sleet is seldom, if ever, encountered at this location. The right-of-way for this line is from 6,000 to 7,000 feet in elevation. The rainfall varies from 9 to 15 inches per year.

Good practice requires that the number of insulators used per insulator string should be such that:

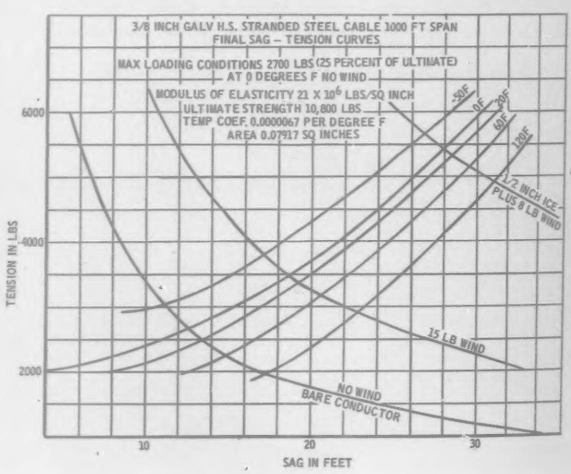
a. The 60-cycle wet flash-over equals or exceeds the voltages which are apt to be encountered from faults or switching surges.
b. The impulse flash-over must be coordinated with the ground resistance in order to keep the trip-outs from lightning to a minimum, and with the basic insulation level of the substation equipment.

Under the most optimistic conditions, the low frequency over voltages to be expected from faults or switching surges are from 3.0 to 3.5 times the normal line to neutral voltage, assuming that the neutral is solidly grounded. Under less favorable conditions, these over voltages may be higher. The average practice at 138 kv is to use nine insulators which corresponds to 4.5 times the normal line-to-neutral voltage. The minimum number of insulators which has ever been used at this voltage is eight. Since this line will be at an elevation of some 7,000 feet, the minimum number of insulators that can be considered is nine, this being equivalent to eight insulators at sea level. The insulation correction factor at this elevation is .89 according to the ASA standards. Nine insulators have a 60-cycle wet flash-over value of 333 kv at 7,000 feet elevation, corresponding to about 4.2 times the normal line-to-neutral voltage which is considered satisfactory. The impulse value of nine insulators at 7,000 feet elevation is 765 kv.

The terminal equipment has an insulation level of 161 kv on a sea level basis, which is equivalent to an



SAG-TENSION curves for 636,000 C.M. ACSR conductor based on different conditions of wind, loading, and temperature. **(FIGURE 5)**



SAG-TENSION curves for 3/8-inch galvanized steel grund wire under similar conditions as those in Figure 5. **(FIGURE 6)**

impulse value of 665 kv at 7,000 feet elevation. The impulse level of the nine insulators is above that of the terminal equipment, as it should be. Therefore, since nine insulators were used, they satisfied both the 60 cycle wet flash-over and the impulse values at this elevation.

Weather controls clearances

The spacing between conductors and the supporting structure should be such that the full strength of the insulator strength is developed. However, due to the possibility of the wood crossarms and the poles splitting, it is desirable to have the flash-over from the conductor to the downlead through air rather than via the insulator string, crossarm and pole. If we assume a flash-over through air equal to the insulator flash-over, the additional insulation provided by the wood will insure that the flash-over will take place through the air. With an insulator impulse flash-over of 765 kv, the distance from the conductor to the pole should be about 54 inches. This clearance should be maintained with the worse wind condition that is expected during a thunder storm.

Records indicate that storms are most numerous in May, June, July and August, with the strongest wind expected during this time to reach a velocity of 55 miles per hour. Winds of this velocity will cause a side swing in the insulator string and conductor of about 40 degrees. With this side swing and a 54-inch clearance to the pole, the spacing between the conductors becomes about 16 feet 6 inches. With this spacing, the clearance to the pole with a 15-pound wind (77.5 miles per hour) would be 42¾ inches which is sufficient providing there is no lightning at that time. As stated before, the records show that the months of highest wind velocities and the months of highest number of thunder storms are not coincident.

The spacing between the conductor and ground wire at midspan is dependent upon:

a. The relative mounting heights of conductors and ground wires.

b. The relative spacing of the conductors and ground wires.

c. The relative sag of the conductors and ground wires.

The most practical manner in which to mount ground wires on an H-frame structure is to extend the pole heights above the crossarms. The shielding cone provided by the ground wires should be such that the conductors fall within an angle of approximately 30 degrees from the vertical with the conductor spacing indicated above. If the ground wires are supported on pole extensions nine feet above the crossarm, the conductors will fall within the desired protective angle of about 30 degrees. Using the dimensions indicated above for the support of the ground wires and conductors and calculating the sags of both the ground wires and conductors (Figures 5 and 6), the minimum midspan separation can be determined. In this particular case, the minimum midspan separation was over 24 feet. With this spacing, the possibility of flash-overs between conductors and ground wires is low. The ground wires chosen were ⅜-inch diameter stranded, high-strength galvanized steel. Each ground wire was connected

SYNCHRONOUS CONDENSERS can be controlled. This 42,000/17,500-kva, 13,800-volt hydrogen-cooled condenser with its rotary type regulator provides flexible voltage control for a West Coast transmission system substation.

to ground at each pole by means of a ground wire down the pole.

The line was designed on the basis of a tension of 8750 pounds in each conductor wire for the "B" loading condition and a tension in each ground wire of 2700 pounds at zero degrees F. These values result in the lowest cost line and a minimum of pole breakage and ground wire fatigue failures.

Ground resistance reduced

The ground resistance which was encountered tends to be high due to the mountainous country and the low rainfall. Studies were made to determine what ground resistance could be expected and what ground resistance was necessary in order to obtain satisfactory line operation. Calculations indicate that if four 10-foot long, ¾-inch diameter rods were driven at each structure, ground resistance would be something in the order of 100 ohms.

A ground resistance of 100 ohms is much too high since the number of interruptions to be expected from lightning at this value would be well over ten per year. It was, therefore, necessary to install some counterpoise in order to reduce resistance. This procedure was found necessary on similar lines previously installed under these conditions. Calculations indicate that with the line design as outlined above and a ground resistance of 30 ohms, the trip-outs per year due to lightning would be something in the order of 1.0. Calculations also indicate that four 60-foot long counterpoise wires buried one foot in the ground will give a ground resistance of about 30 ohms in a dry season. Therefore, such a counterpoise was installed at each structure.

Consideration was given to the possibility of installing an additional insulator to each string, in order to accomplish the same result as lowering the ground resistance. Comparative estimates, however, showed that this would cost approximately 50 percent more than to lower the ground resistance.

Either armor rods and vibration dampeners or both were supplied at each conductor clamp to reduce the fatigue which would occur in the strands at this point if these precautions were not taken.

The corona loss for a line of this design and elevation is very small, something in the order of .2 kw per three phase mile.

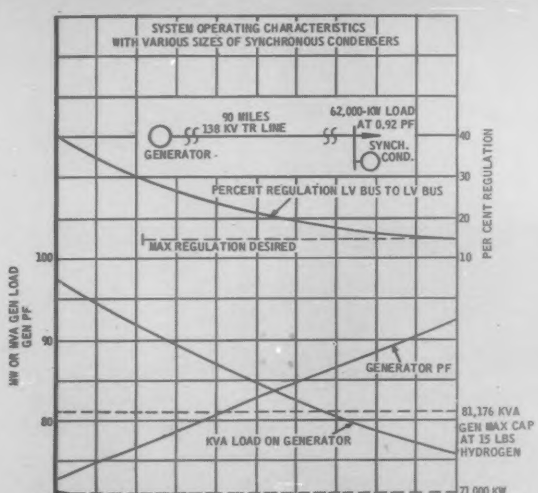
Synchronous condensers can be regulated

Calculations based on Figure 7 indicate that it would be necessary to install a 25,000-kva condenser. Static condensers were considered but this type of condenser has just the opposite characteristic from what is desired, i.e., having their capacity reduced when the voltage is lowered at a time when additional condenser capacity for an installation of this nature is needed. Also, static capacitors of this rating would cost more than a synchronous condenser. For these reasons, static capacitors were impractical.

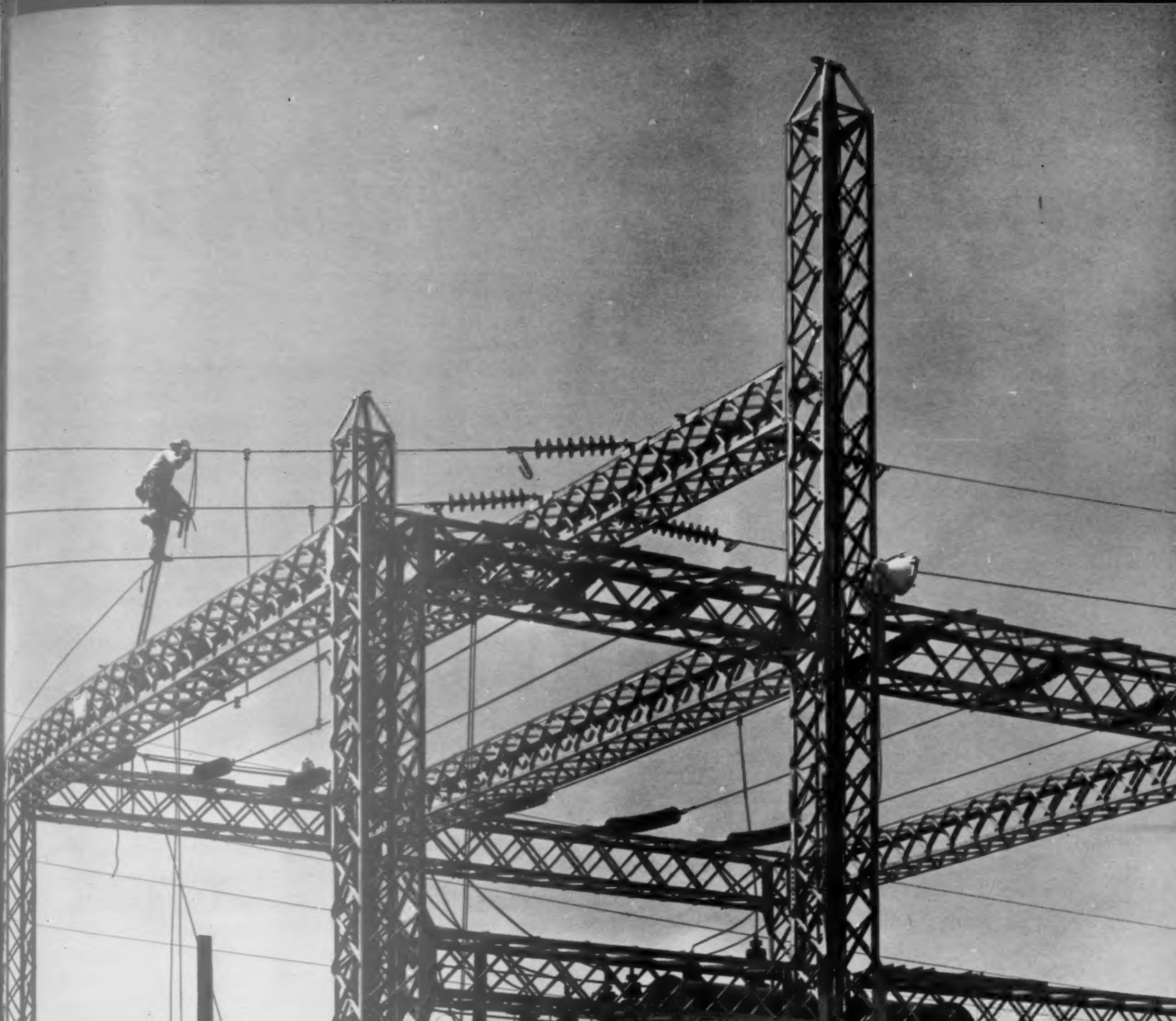
Attention was directed to studies of smaller sizes of synchronous condensers as well as the possibility of transmission with no condenser. Studies revealed that it would be necessary to have a 25,000-kva condenser to limit the regulation in the line and transformers and to keep the load on the generator within the capabilities of the machine. A hydrogen-cooled condenser was chosen and installed out of doors. Provided with an automatic voltage regulator, the condenser automatically regulates the voltage and the supply of reactive current during normal operations and during system disturbances. If this system is to be interconnected with other systems, the condenser will aid materially in the regulation and control of the flow of reactive power between systems.

Stability is considered

The transient stability problem is not serious since the load is relatively steady, and the problem was very much simplified because this system was not interconnected with other systems or generating plants. Circuit breakers and relays of modern normal speed were used to protect the system. Modern high-speed automatic voltage regulators were used on both the generator and synchronous condenser. These provisions enable the system to ride through any disturbances with a good margin of safety. The maximum power limit of this transmission system from the viewpoint of a steady-state stability is something in the order of 166,000 kva. Since 67,500 kva is the maximum power which is to be transmitted, the system is being operated well within the steady-state stability limit.



SELECTION OF SYNCHRONOUS CONDENSER rating is based on limiting regulation in line and transformers and avoiding overload on generator. Calculations show that any condenser smaller than 25,000 kva will not provide adequate regulation. **(FIGURE 7)**



HOUSTON LIGHTING AND POWER CO.'S new 50,000/66,667 kva autotransformer is one of the nation's really big transformers. The unit ties together the utility's 132 and 66 kv systems and provides ± 10% load-ratio-control at the latter voltage. A 15,000/20,000 kva, 12 kv delta connected tertiary winding provides interconnection for power and power factor correction. All of this adds up to a transformer approximately 24 x 17 ft by 26 ft high overall, weighing 232 tons.

DOUBLE-ENDED SUBSTATION *Economy or Luxury?*

by **J. V. McGUIRE**
Manager
Unit Substation Section
Allis-Chalmers Mfg. Co.

Double-barrelled reliability at every substation in an industrial plant may cost more than it's worth.

DOUBLE-ENDED UNIT substations have found wide application in industrial plants requiring a highly reliable power supply. With double-ended substations, maintenance, inspection and testing of transformers, primary equipment and low voltage breakers can be done without power interruption.

There are many plants, however, where a short shutdown for maintenance can be tolerated without loss or inconvenience. The use of double-ended unit substations in such plants adds thousands of dollars of unnecessary expense.

Units provide double protection

The double-ended unit substation is one having two transformers feeding two sections of low voltage switchgear separated by a normally open tie breaker. Figure 1 shows the most common arrangement of a double-ended unit substation. The single line diagram of such a unit is shown in Figure 2.

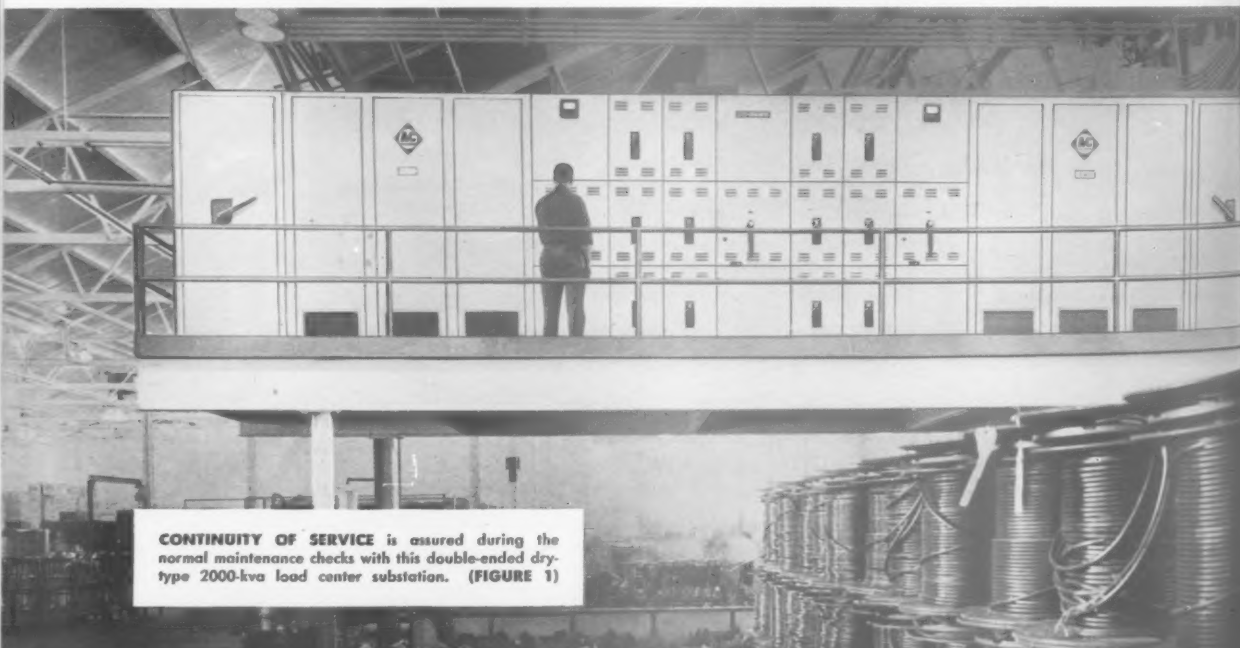
A double-ended substation may have two separate units installed face to face with a common operating aisle and with a low voltage bus run tying the two units together. In other cases two units are located some distance apart and tied together by lengths of low voltage cable. In each case the one line diagram is essentially that shown in Figure 2. Double-ended unit substations usually are specified in an attempt to increase the reliability of the unit.

How is reliability increased? The double-ended unit substation provides emergency service for two basic failures:

1. Failure of one transformer.
2. Failure of one incoming line.

In case of either type of failure, the operator must manually trip the transformer secondary breaker on the faulted side of the substation and then manually close the tie breaker. The second transformer then takes over the load of the entire substation. Such an operation requires:

1. An outage must be tolerated from the time of failure until the load is picked up manually.
2. Each transformer must be equipped to carry the total load of the station. This usually means oversize transformers plus fans, or
3. Some load must be dropped during emergency operation.



CONTINUITY OF SERVICE is assured during the normal maintenance checks with this double-ended dry-type 2000-kva load center substation. **(FIGURE 1)**

To provide service despite the failure of the primary line feeding one transformer, there is the additional requirement that the opposite ends of the substation be fed from two separate high voltage cables.

At first, these provisions for emergency service may sound like fairly good recommendations for the double-ended unit. However, consider the cost of making these provisions.

Safer, but more expensive

The basic source of high cost in this type of substation is the two main breakers and the tie breaker that are used and are not required in two single-ended units. Without these three breakers, the double-ended unit substation becomes two single-ended radial units. The main breakers usually are larger than the feeder breakers, not because of interrupting capacity requirements, but because each must carry the full load current of the transformer. The high cost of these breakers can be seen best from a specific example. Figure 2 is the single line diagram of a 3,000-kva double-ended unit substation, a size and arrangement very commonly used in automotive and other large industrial plants. If this substation were built as two single-ended units, the three 75,000-amp interrupting capacity breakers could be eliminated. The single line drawing of this unit is shown in Figure 3. Figure 4 presents the cost comparison of the double-ended station against two single-ended units.

To show that the 3,000-kva unit is not just a fluke, the additional set of bars on Figure 4 represents a similar comparison between a double-ended 600-kva unit with a secondary of 208Y/120 volts, intended for lighting service, and two 300-kva units. The relative costs in these two examples are typical of those encountered in industrial unit substations. It is apparent that a very large saving usually can be made by substituting two single-ended units for one double-ended unit.

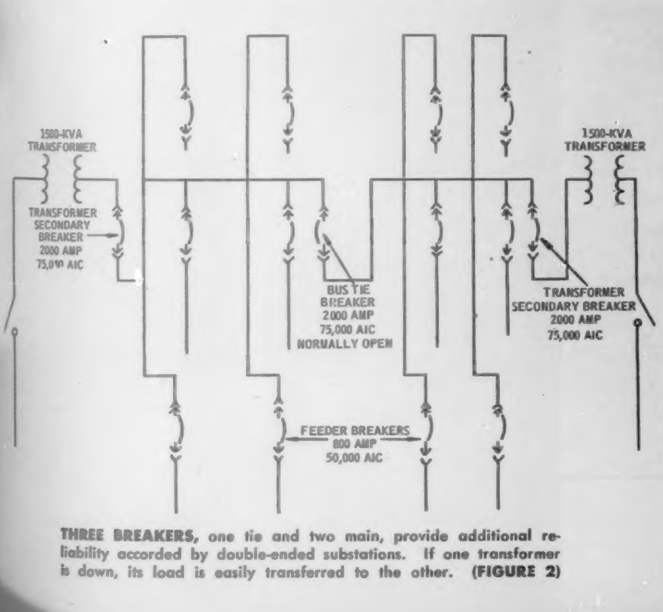
Each of the examples assumes that the feeder breakers will not be cascaded, that each feeder breaker will be capable of interrupting the maximum fault current to which it will be subjected. When the feeder breakers are cascaded, the savings shown are not so great. However, the operating disadvantage of cascading often precludes its use.

Single-ended units are often adequate

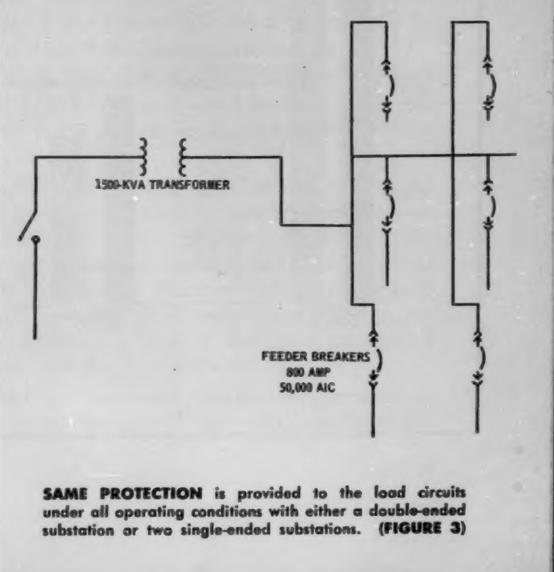
It is probably evident, at this point, that the substation cost can be reduced appreciably by using two single-ended substations rather than one double-ended unit. It must be equally apparent that this economy was effected at the expense of the reliability that led to the use of double-ended units in the first place. This situation raises the question as to whether or not this reliability can be regained in the single-ended units at a more reasonable cost.

The primary selector switch shown in Figure 5 is a direct and economical way of providing for primary cable failure. Half of the transformers in an industrial plant use cable A as normal feed and the other half use B. In case of failure of cable A, those on cable A are manually switched to B. Since this is a simpler switching operation than is required on the double-ended unit, it can be accomplished more rapidly in an emergency. Furthermore, the transformer can still carry full load without being oversize or using fans. This is an extremely important operating advantage of the selector switch arrangement. Primary cable costs are about the same for one double-ended unit or two single-ended units. The selector switch costs more than the simple disconnect but the increase is considerably less than the saving on a low voltage breaker.

The operating record of modern transformers is such that extensive provisions for operating in case of transformer failure are of questionable value. Emergency cables can be used to effect the same operating conditions as a double-ended unit. For example, the joint between



THREE BREAKERS, one tie and two main, provide additional reliability accorded by double-ended substations. If one transformer is down, its load is easily transferred to the other. **(FIGURE 2)**

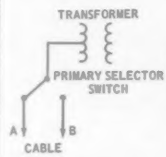


SAME PROTECTION is provided to the load circuits under all operating conditions with either a double-ended substation or two single-ended substations. **(FIGURE 3)**

the faulted transformer can be disconnected manually without too much difficulty since bare copper bus is used in these units. Tie cables may be run from a spare breaker position or the bus in a nearby unit to the bus of the faulted unit. This can be done at no increase in substation equipment cost. The operating conditions will be exactly the same as for a double-ended unit under similar conditions. Installing the emergency cable, however, will take longer than manually operating the main and tie breakers of a double-ended unit. This must be weighed against the saving in equipment cost, remembering the good service record of modern transformers.

Spare transformer for extra protection

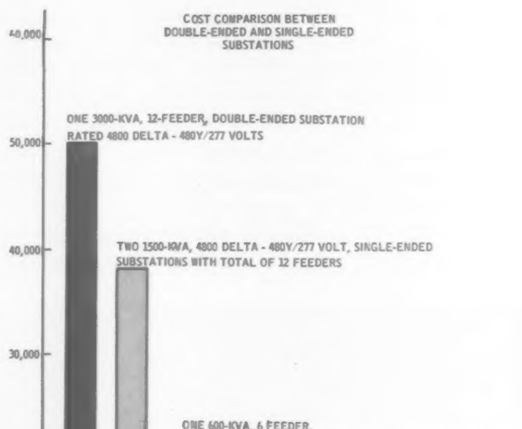
If transformer failure is still a worry, a small part of the savings realized by using single-ended units might well be invested in a spare transformer. The spare unit would always be available to provide extra transformer capacity whenever needed. The cost would be only a small part of the savings in a large plant. For example, the 1500-kva



PRIMARY SELECTOR SWITCH can be used to assure continuity of service where cable failure is a possibility. **(FIGURE 5)**

transformer of Figure 2 costs only $10,240.00. The saving realized by going to single-ended construction in just this one station is $11,750.00!

A review of the conditions surrounding the use of double-ended units indicates that they are not always the best nor the most economical way of providing a reasonable degree of reliability in industrial unit substations. In some cases they are the only satisfactory means of meeting certain load conditions. Before a final decision is made in favor of double-ended units, their cost should be compared carefully with that of two single-ended units.



MAJOR CUT is made in substation cost, regardless of size, by using single-ended units instead of double. Double-ended substation reliability may not be warranted. **(FIGURE 4)**

TWO SINGLE-ENDED SUBSTATIONS serve where one double-ended unit might be used. The 500-kva unit (left) and 1000-kva unit (right) are completely independent. **(FIG. 6)**

VISUALIZING TRANSFORMER IMPEDANCES

by **W. C. SEALEY**
Engineer-in-Charge
Transformer Design
Allis-Chalmers Mfg. Co.

This novel technique shows at a glance the relationship between impedances in a three-winding transformer.

THREE-WINDING TRANSFORMERS are often used on present-day transmission lines. Equivalent circuits and the algebraic equations derived from them are used to determine the performance of the transformers for a given application. Although they are very useful, such devices do not present the relationship between the impedances of the equivalent circuit in simple terms which are easy to visualize.

The various impedances of the equivalent circuits are mutually related and, although considerable variation in their values is possible, there are limitations on the combinations of impedances which may exist. In order to help in visualization, a diagram has been prepared to show these limitations. The application engineer can readily see what variations in impedance are possible and how a change in one impedance affects the other impedances of the equivalent circuit.

Limitations shown by mathematics or graph

The most common equivalent circuit used for three-winding transformers is the star diagram shown in Figure 1. Values for the equivalent circuit are derived by solving three equations simultaneously:

Impedance from wdg. A to B $= Z_{ab} = Z_a + Z_b$
Impedance from wdg. B to C $= Z_{bc} = Z_b + Z_c$
Impedance from wdg. A to C $= Z_{ac} = Z_a + Z_c$

Solving:

$$Z = \tfrac{1}{2}(Z_{ab} + Z_{bc} + Z_{ac})$$
$$Z_a = Z - Z_{bc}$$
$$Z_b = Z - Z_{ac}$$
$$Z_c = Z - Z_{ab}$$

The mesh or delta equivalent circuit shown in Figure 2 is used less frequently.

Analysis of the equivalent circuit of Figure 1 is facilitated by the use of a diagram drawn to scale such as shown in Figure 3.

To construct this diagram Z_a and Z_c are laid out to scale on the same horizontal line, point O representing the junction between them. Z_b is drawn on the vertical line erected at O. Positive values of Z_b are plotted upward and negative values plotted downward. In this diagram the impedance from winding A to winding B is equal to the algebraic sum of Z_a and Z_b which is equal to the distance AO + the distance OB. (Note that it is not the geometrical straight line distance from A to B.)

Such a diagram can be constructed from values obtained by solving the equations for Figure 1 by algebraic methods using the equations given above. It can also be constructed graphically if desired.

Transformers may be designed to meet a wide variety of desired impedances. However, there are some inherent limitations imposed by the fact that a transformer contains only inductance and resistance, and consists of coils having self and mutual inductance. These limitations are fundamental and apply to all transformers. They do not include such limitations as exist because of the type of construction used for the transformer.

Whenever the impedance between two windings is greater than the sum of the other two impedances be-

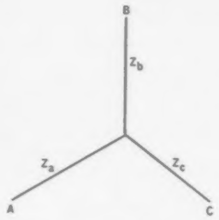


FIGURE 1

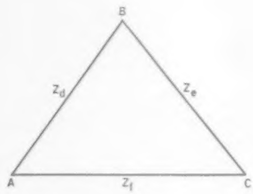


FIGURE 2

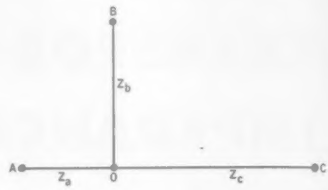


FIGURE 3

tween windings, the equivalent impedance of one winding is negative. This is a common occurrence since frequently the highest impedance is slightly greater than the sum of the other two.

Only one of the values Z_a, Z_b, and Z_c can be negative. If two of the windings could have negative impedances, then the impedance between the two windings having negative impedances would be negative, which is an impossible situation for a device containing only inductance and resistance.

Impedance limits pictured

The clearest diagram can be drawn when Z_a and Z_c are both positive and Z_b is either positive or negative, as shown in Figure 4. The most general diagram is that shown in Figure 5 where either Z_a, Z_b or Z_c can be negative.

This diagram is useful because it shows the possible relationships which can exist between the individual impedances assigned to each winding and the total impedance between windings.

In Figure 4, points B+ or B− must lie in the unshaded area. A perpendicular line drawn from point B to line AC determines point O. For a fixed value of AC, when both Z_a and Z_b are positive, this diagram includes all the combinations of transformer impedances which are possible. The relationship between the impedances between windings and the leg impedances in the equivalent diagram is at once apparent.

The following analysis shows the reason for the shape of the diagram of Figure 4. If point B extended into the shaded area, the total impedance from A to B which is the algebraic sum of AO and OB, would be negative. Since the transformer winding contains only inductance, the total impedance from one winding to another must always have a positive value of inductive reactance. Consequently the boundary of the shaded portion is formed by lines 45 degrees from line AC. In Figure 4, if point B were to lie to the left of the vertical line through A the value of AO would be negative. Since this diagram is confined to positive values of AO and CO, the boundaries for the diagram are vertical lines through A and C.

In Figure 5, the values of AO and CO are not restricted to positive values so that the boundary of the shaded portion is formed by the extension of the two 45-degree lines in Figure 4. If point B in Figure 4 and Figure 5 were in the shaded area, the result would be a negative value for the impedance from winding B to one of the other windings. This is an impossible condition in a transformer, since the impedances consist of only inductive reactance and resistance.

The general diagram of Figure 5 is not as convenient to use but it represents all possible combinations of transformer impedance. As before, point B must lie in the unshaded area and may be located anywhere in this area. A perpendicular line is drawn from B to either line AC or its extension. As before, positive values of BO are those where the point lies above line AC; negative values where point B lies below line AC. When line AO or line CO is partly in the clear space, their values are positive. When either of these lines are entirely in the shaded area their value is negative. For the case shown in Figure 5, CO is negative but AO and BO are positive.

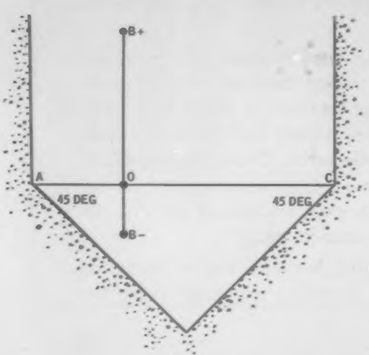


FIGURE 4

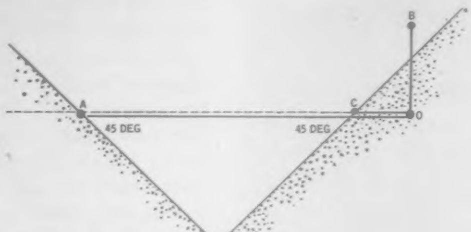


FIGURE 5

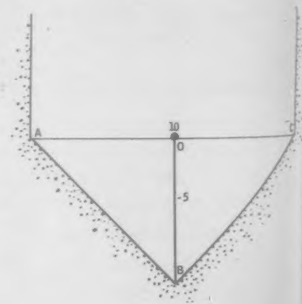


FIGURE 6

Figure 5 is shown mainly for completeness and for use in exceptional cases. In most cases the diagram of Figure 4 can be used.

Diagrams illustrate use

Such a diagram drawn to scale will show at once whether a desired impedance combination is possible. For example, if it is desired to have the impedance Z_b equal to zero, it is evident from the diagram that the impedance Z_{ac} must be equal to the sum of the impedance Z_{ab} plus Z_{bc}. Several examples are given to show how such diagrams may be used.

Suppose that the impedance from winding A to C is 10 percent, what is the maximum possible negative value of B?

Figure 6 is drawn to scale with the line AC equal to 10 units. By inspection it is obvious that the maximum negative value of Z_b is one-half of AC or 5 percent. It is also obvious that this maximum negative value of Z_b can be obtained only when the impedance Z_a equals the impedance Z_c. (Actually a maximum impedance value of 5 percent is not obtainable because under these conditions the impedance from A to B would be zero and the impedance of B to C would be zero, but values approaching this limit are possible.)

If the impedance from A to C is 10, the impedance from A to B is 5, and Z_a and Z_c are positive, what variations are possible in impedances Z_a, Z_b, and Z_{bc}?

Figure 7 is constructed to scale. It will be noted that the positive values of impedance Z_a must lie between 0 and 7½ percent. Corresponding values of Z_b vary from 5 to minus 2½ percent. Under these conditions the value of the impedance Z_{bc} will lie between 15 percent and 0 percent.

If the impedance from A to C is 10 percent and it is desired to have a minimum impedance from A to B of 3 percent and from B to C of 4 percent, what are the maximum possible negative and positive values of Z_b?

Figure 8 shows that the limit on the maximum negative value of Z_b is 1.5 percent as shown by the point B_2. There is no limit on the maximum positive value of Z_b.

If a transformer has $Z_{ac} = 10$, $Z_{ab} = 6$, $Z_{bc} = 8$, and consequently leg impedances $Z_a = 4$, $Z_c = 6$, $Z_b = 2$, is it possible to leave Z_{ac} equal to 10 and increase Z_{ab} without increasing the impedance Z_b?

Figure 9 shows how the problem can be solved. From the diagram it is evident that the impedance Z_{ab} may be increased leaving the impedance Z_b at 2 percent, by moving B along the dotted line. As Z_{ab} is increased, Z_{bc} is correspondingly decreased. By inspection, one possibility is $AO = 8$; $CO = 2$; $BO = 2$ resulting in $Z_{ac} = 10$, $Z_{ab} = 10$, and $Z_{bc} = 4$.

The principal value of such diagrams lies in their showing all of the possibilities graphically and giving the solutions directly by inspection.

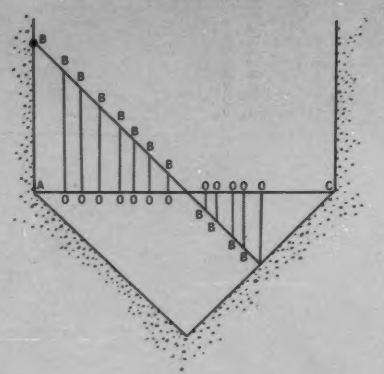


FIGURE 7

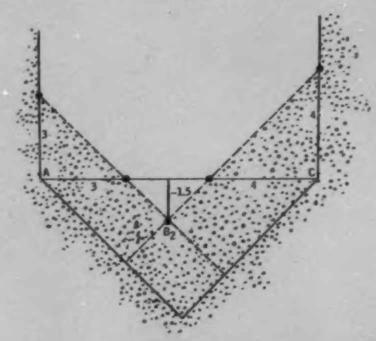


FIGURE 8

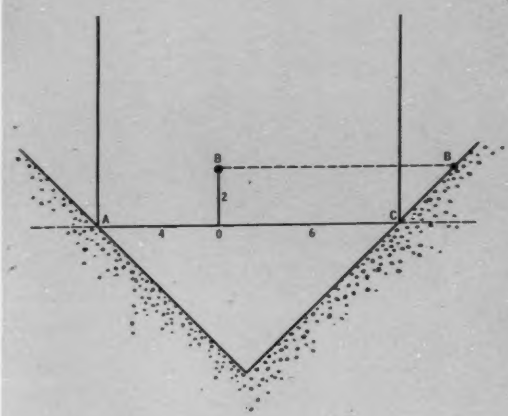
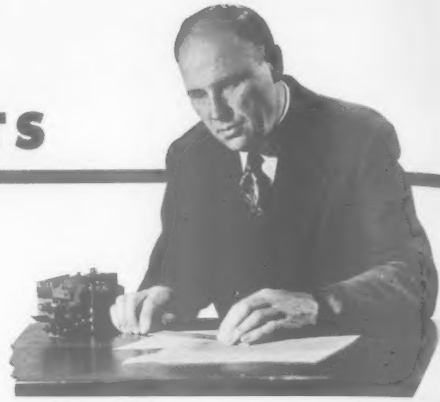


FIGURE 9

ON THE FOLLOWING PAGES the graceful lines of the Kaplan runner shown on the cover can be seen. The rotor will operate at 81.8 rpm under 43 ft head.
A-C Staff Photo by M. Durante

NOMOGRAPHS

BY-PASS TEST COSTS



by **JOHN BAUDE**
Engineer
Switchgear Section
Allis-Chalmers Mfg. Co.

Read how hours of test and set-up time is cut to minutes by graphic analysis of everyday problems.

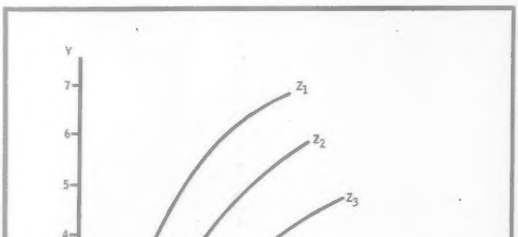
NOMOGRAPHS OR ALIGNMENT CHARTS have been used for many years for solving simple problems involving inductance, capacitance, reactance and frequency. With a few preliminary steps, the use of nomographs can be extended far beyond these simple problems. With the usual alignment chart, each scale represents a variable, and the scales are so arranged and marked that a straight line drawn through all of the scales will cross at points which satisfy the equation for which the chart was prepared. Intermediate values of any one variable can be found with respect to the other variables by simply holding a straightedge across the charts at various angles.

Characteristics of new sizes of products can be predicted by graphical interpolation or extrapolation of the known characteristics of a series of other sizes of these products. A series of test curves of a new product or test model can be used to determine the safe limits of operation without damaging costly test models.

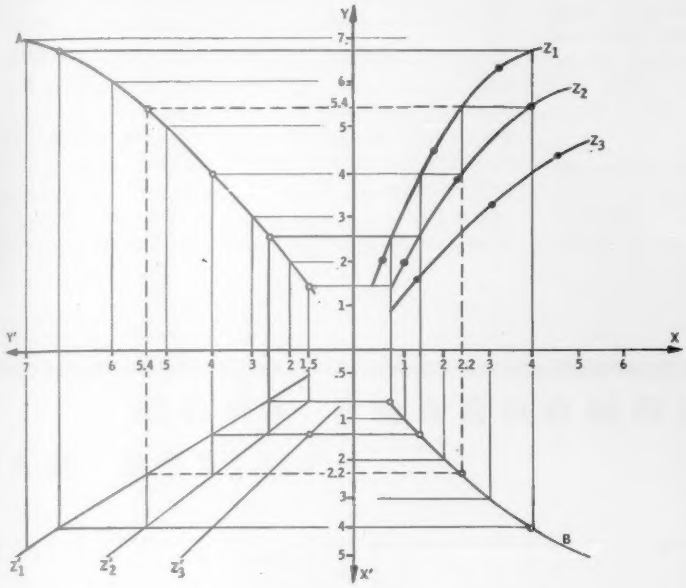
Curves transformed into straight lines

The first step in graphical preparation of a nomograph requires that the curves which are to be analyzed must be transformed into straight lines. One curve in a coordinate system can be transformed into a straight line by distortion of the scale on one axis, and two curves can always be presented as straight lines by distortion of both coordinates. The curves and reference points from Figure 1, which have been transferred into the first quadrant of Figure 2a, are purely imaginary curves that are used to explain the method of changing from curves to straight lines.

Two straight lines, Z1′ and Z2′, were drawn in the third quadrant in a similar direction and position to curves Z1 and Z2 in the first quadrant. These lines represent the curves Z1 and Z2 in the new X′, Y′ coordinate system. The scale points or markings on the new X′, Y′ scales are graphically constructed as shown. Lines resembling steps were drawn at random between Z1 and Z2 curves and between the Z1′ and Z2′ curves starting as close to the zero point as possible. The vertical lines of the steps between Z1′ and Z2′ are extended through the second quadrant. The horizontal step lines between Z1 and Z2 are also extended through the second quadrant. Curve "A" is then drawn through the intersecting points of the vertical and horizontal lines in the second quadrant. Curve "B" is constructed in a similar manner in the fourth quadrant. Points on the Y axis are projected to the curve in the second quadrant. Lines are drawn from these points of intersection to the Y′ axis to obtain the Y′

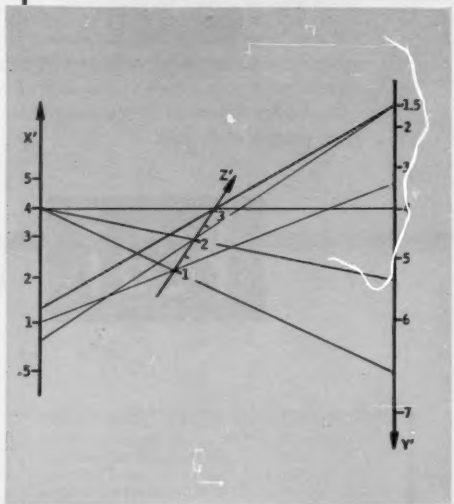


MINIMUM OF THREE CURVES is required for this method of graphically interpolating or extrapolating known data. Where the data results in a set of irregular or oscillating curves, the curves are divided into sections, so simple curves can be obtained. (FIG. 1)



AXIS SCALES of curves in the first quadrant are changed to obtain the straight lines in the third quadrant. **(FIGURE 2a)**

NOMOGRAPH SCALES are obtained from new scales and data developed graphically in the third quadrant. **(FIGURE 2b)**



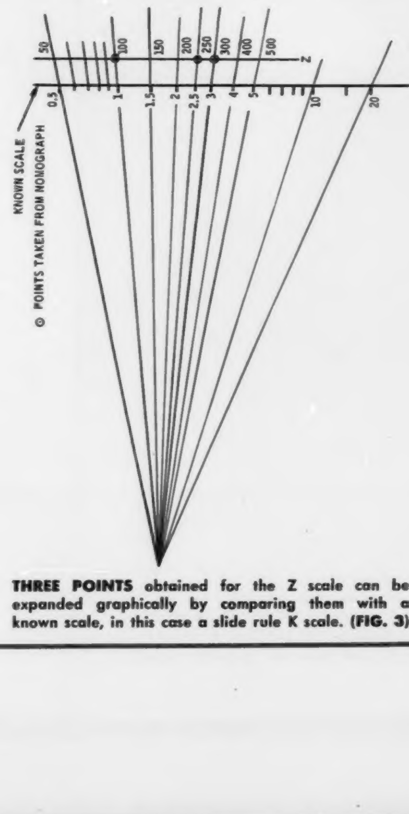
scale points. The X′ scale was constructed in the same manner as the Y′ scales.

The Z3′ line is plotted from the Y′ and X′ axis. If it is straight or almost straight, fair accuracy can be expected. If, however, the Z3′ line is curved, then the original data is erratic and unsatisfactory results can be expected.

To obtain the best possible accuracy, X and Y scales should be chosen to make the Z curves close to straight lines. It is also desirable to choose two curves that are close to each other so that there will be a greater number of steps between curves. If equal original scale markings for the X and Y scales result in curves which are practically horizontal, it is obvious that the X markings should be compressed as compared to the Y marking to give the curves a more vertical position and increase the number of steps between them. This procedure will make the A and B scale curves more accurate.

Transfer scales to nomograph

A nomograph, or alignment chart, in its simplest form consists of three scales representing three variables. The three scales are so located and marked that a straight line drawn from one scale to the next will intersect the third scale at a point which reveals the interrelation of all three variables.



THREE POINTS obtained for the Z scale can be expanded graphically by comparing them with a known scale, in this case a slide rule K scale. **(FIG. 3)**

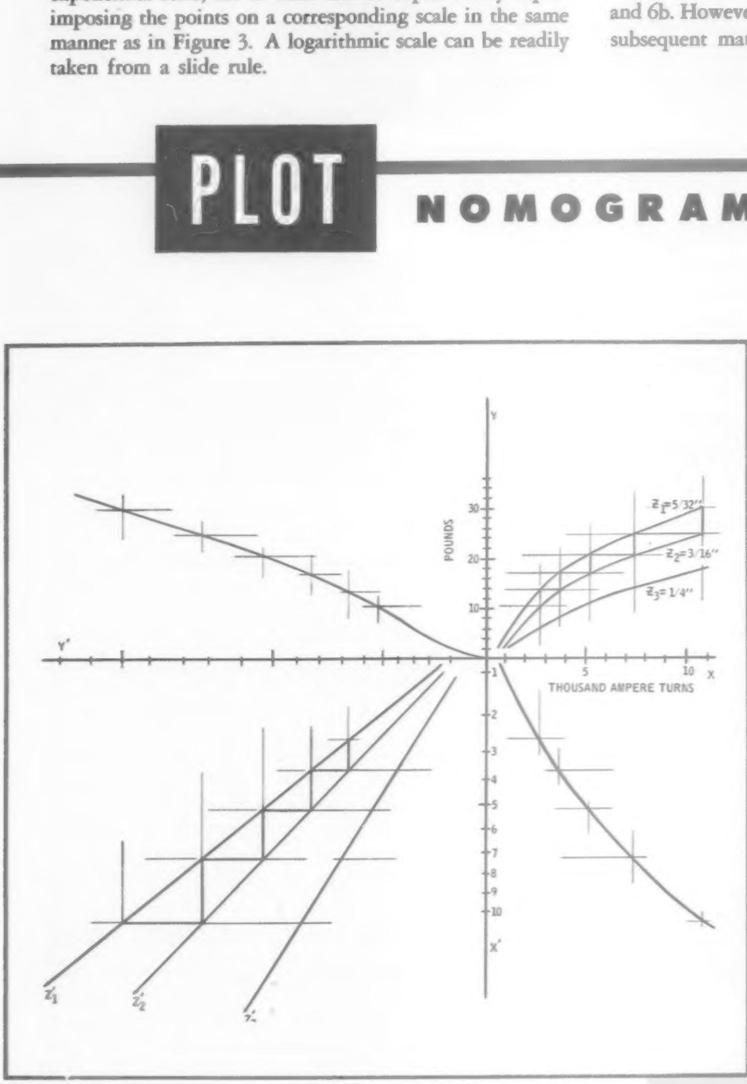
Points for the Z′ scale are found by taking two corresponding sets of X′ and Y′ values for each curve. The Z'_1 curve is used to obtain point 1, the Z'_2 curve to obtain point 2, and the Z'_3 curve to obtain point 3 on the nomograph. Lines between corresponding points on the nomograph will intersect at the three points. If they do not cross, the Y′ axis has the wrong polarity and should be inverted. Points 1, 2 and 3 are used to locate the Z′ line as shown in Figure 2b.

If the three known points follow a linear scale or any exponential scale, the Z′ scale can be expanded by superimposing the points on a corresponding scale in the same manner as in Figure 3. A logarithmic scale can be readily taken from a slide rule.

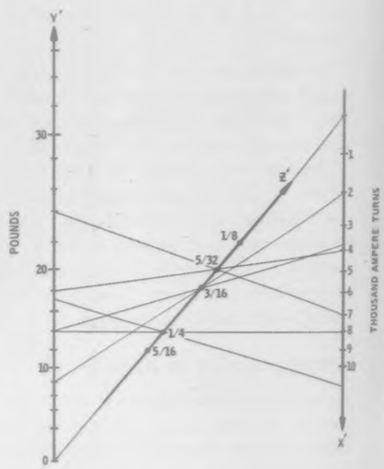
Figures 4a and 4b to Figures 10a and 10b show simple forms of nomographs. The direction in which the Y′ line should be drawn for each type of curve can be found without mathematical analysis by referring to these figures.

In most cases the Z′ scale will be a straight line. However, if the Z lines in the curve chart intersect each other in several points, as shown in Figures 8a and 9a, curves like those in 8b and 9b will occur. It is important to remember that the scale markings X′ and Y′ do not have to be proportional. This condition is shown in Figures 6a and 6b. However, if the scales can be drawn proportionally, subsequent mathematical analysis is relatively easy. The

PLOT NOMOGRAMS FROM LIMITED DATA



DETERMINING PULL characteristics of an ac magnet is simple if three pull curves, each for a different air gap, are available for identical magnet designs.

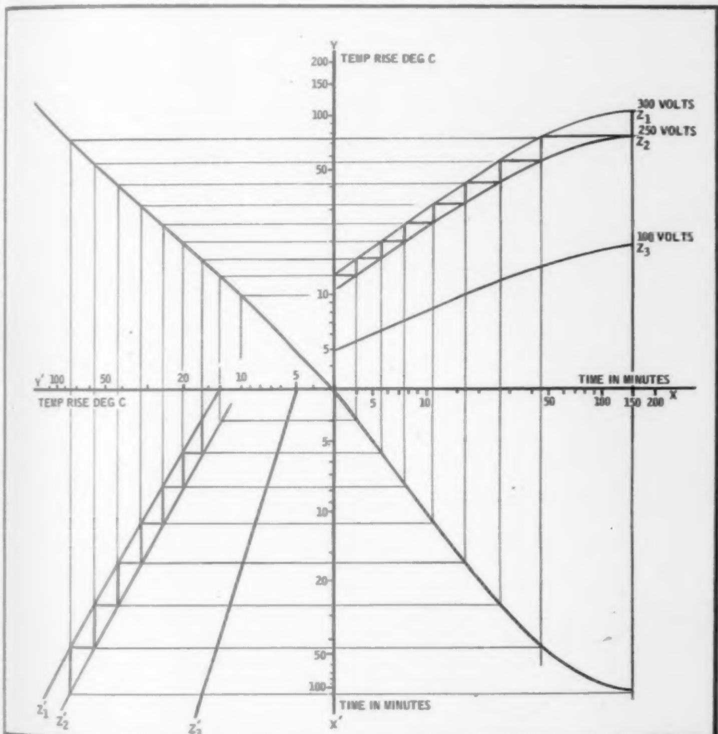


ACCURATE RESULTS can be expected if test data is reliable. This method eliminates involved calculations or cut and try coil design. If the Z scale in the nomograph does not follow some known proportionality, the only way to assume accuracy is to run a check test at a point near the values in question.

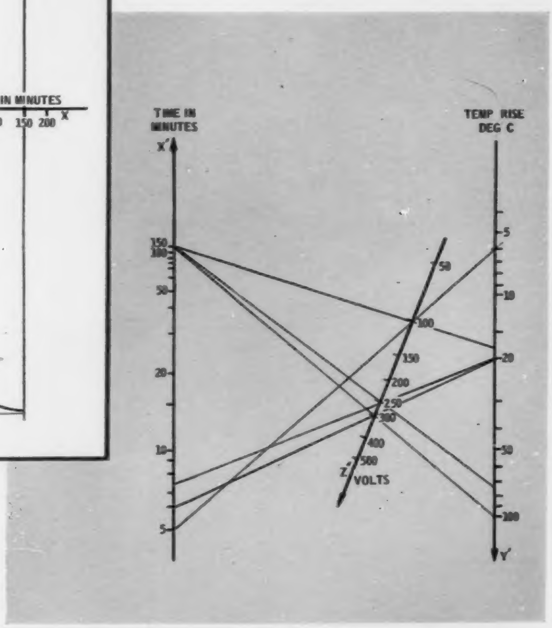
scale then becomes a means by which a curve or straight line can be compared with a simple known mathematical function or formula. Application of this method of expanding known data is shown below.

With simple data like that illustrated in these examples, problems ranging from the design of equipment to problems in chemistry can be solved graphically with considerable savings in time and expense. Generally, it is less expensive to take sufficient data to facilitate the construction of a nomograph by this method than to duplicate a set-up and make further tests at a later date. Temperature tests usually fall in this category.

TYPICAL CURVES AND CORRESPONDING NOMOGRAMS



TEMPERATURE RISE in coils and other current carrying parts during short time overloads can be readily predicted from test data taken at normal overloads. Logarithmic scales were used to obtain curves that approximate straight lines for the dc relay coil characteristics shown. This method provides greater plotting accuracy.



COIL TEMPERATURE characteristics for this relay are obtained by simply moving a rule across the nomograph. Both short and long time temperature characteristics are found at a glance. The voltage scale was expanded by the methods shown in Figure 3.

VARIOUS COMBINATIONS of curves result in a diversity of nomographs. These examples show the common types of nomographs that may be developed from similar curves. Shape and direction of curves determine nomograph scale polarity. (FIGURES 4a to 10b)

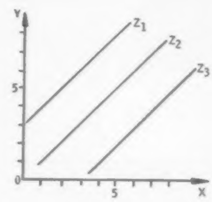


FIGURE 4a

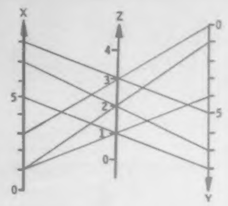


FIGURE 4b

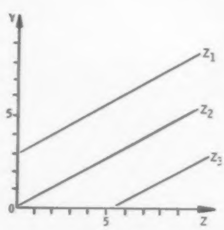


FIGURE 5a

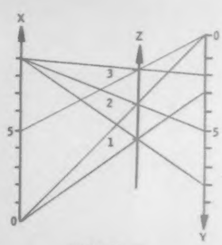


FIGURE 5b

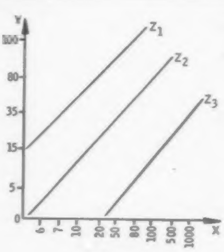


FIGURE 6a

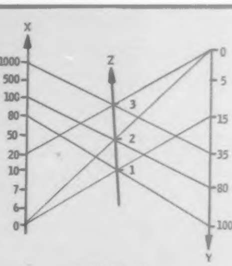


FIGURE 6b

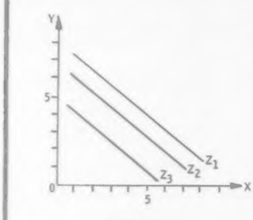


FIGURE 7a

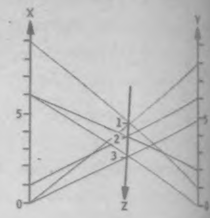


FIGURE 7b

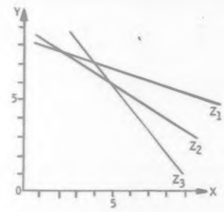


FIGURE 8a

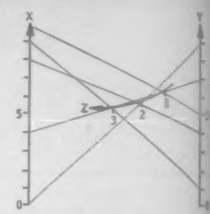


FIGURE 8b

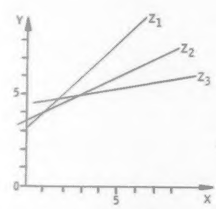


FIGURE 9a

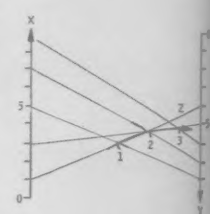


FIGURE 9b

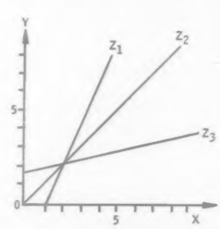


FIGURE 10a

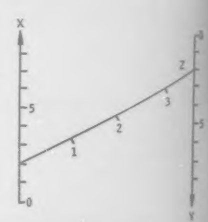


FIGURE 10b

MODERNIZATION OF MILLS AND REFINERIES in the nation's basic industries has been going forward at an amazing rate since 1945. Here, one of five new rod mills is being installed in a midwest lead mill. Replacing less efficient crushing rolls, the mills, driven by 450 hp synchronous motors, will process 15,000 tons of ore per 24 hour day.

Paralleling Synchronous Frequency Changers

by H. H. ROTH
Engineer
Motor-Generator Section
Allis-Chalmers Mfg. Co.

Watch pole displacement when paralleling synchronously driven frequency changers.

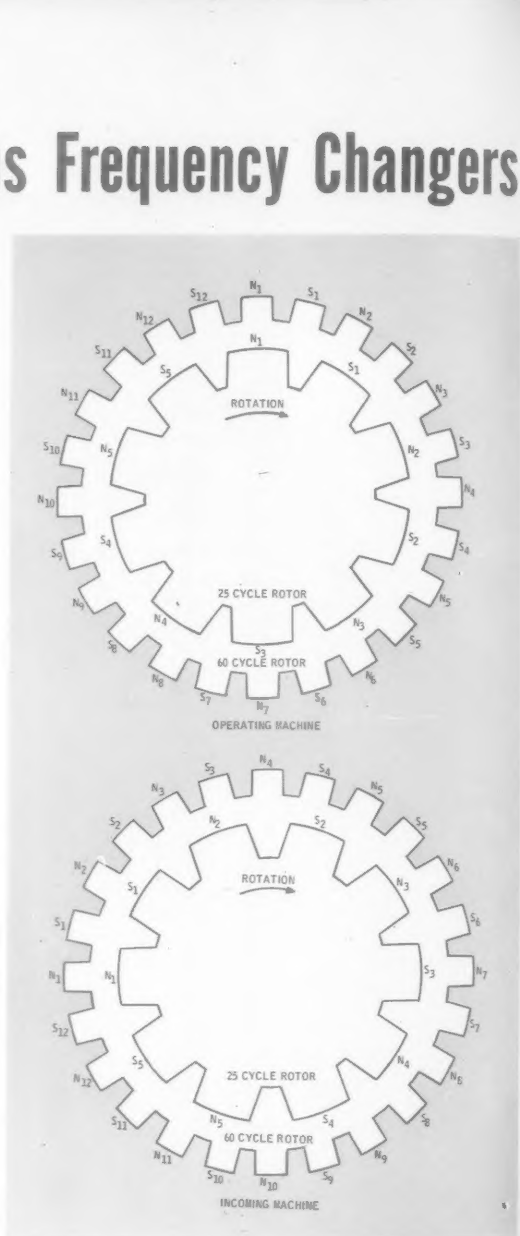
A SYNCHRONOUS FREQUENCY changer set consists of a synchronous motor coupled to a synchronous generator. Each unit operates in an entirely normal and relatively simple manner. However, when two or more synchronous frequency changer sets are to be operated in parallel, certain problems arise. Frequently these are not appreciated until parallel operation is attempted.

If a synchronous frequency changer set is in operation, and it is desired to parallel another set with it, an immediate problem may be encountered. The motor of the incoming set is started in the usual manner and field current is applied to pull it into synchronism. Field current is then applied to the incoming generator, but it may not be possible to synchronize the two generators due to a phase displacement between them.

Pole displacement causes problems

This condition may be more easily understood by reference to Figure 1, which shows the relative pole positions of both machines of two 60-to-25-cycle, 300-rpm frequency changer sets. Assuming that the 60-cycle machines are the motors, if field current is applied so that Pole N4 of the incoming machine assumes the same physical angular relation as pole N1 of the operating 60-cycle machine, it will not be possible to parallel the two 25-cycle generators, since they will be 90 electrical degrees out of phase.

A study of Figure 1 will show that either pole N1 or N7 of the incoming 60-cycle motor must have the same physical angular relation with pole N1 of the operating 60-cycle motor in order that the poles of the two 25-cycle generators are in proper position to permit synchronizing. If pole N1 of both 60-cycle motors happen to have the same angular position, the 25-cycle generators can be synchronized at once. If poles N7 and N1 of the respective incoming and operating 60-cycle motors have the same angular position, then poles N1 and S3 of the 25-cycle generators will also have the same angular position. In this case if the excitation polarity of the incoming generator is reversed, S3 will become a positive pole and the generators may be parallel.



PROPER POLE DISPLACEMENT between incoming and running frequency changers is not assured. The incoming set's synchronous motor may not pull in step with correct pole relationship. (FIG. 1)

Since the incoming 60-cycle motor may pull into step in 22 other angular positions with respect to the operating motor, it may be seen that there is only one chance in eleven of having the correct angular positions for synchronizing both ends of two sets on the first attempt. The incoming machine may be brought to the correct angular position by reversing the polarity of its excitation the proper number of times, since the motor will slip a pole each time the excitation is reversed. Field reversing switches on the control panels of both sets are used for this purpose.

When two or more synchronous frequency changer sets are to be operated in parallel, it is customary to provide all but one of the sets with a frame shifting device. This consists of a hydraulic or motor operated mechanism by which the stator of the higher frequency machine of a set can be rotated to a limited extent. This permits adjusting the division of load between sets during operation by physically moving the stator ahead or back of its normal position. The paralleling of two sets is also more easily accomplished with this device, since the amount and power factor of the load on the operating machine will cause a shift between the magnetic axes of the two generators. By proper rotation of the stator of the incoming 60-cycle motor, the magnetic axes of the two generators may be brought together, even if the operating generator is loaded.

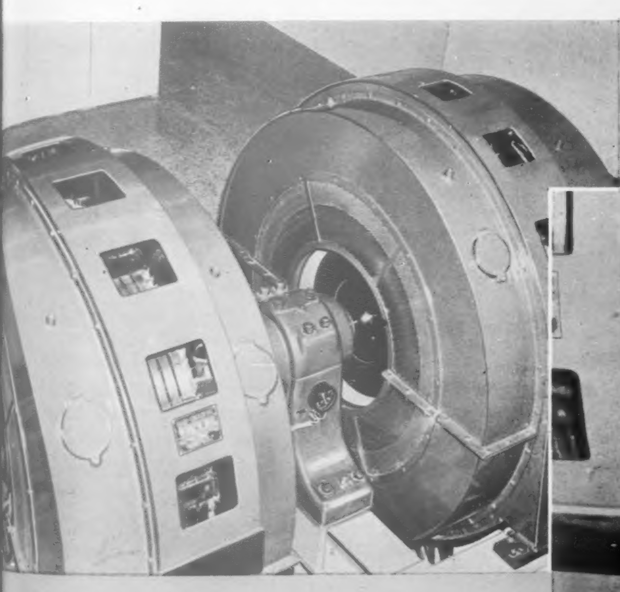
Phase shifting device corrects displacement

The phase displacement or relative angular positions of the two generators may be checked by use of a synchroscope supplemented by a voltmeter for accurate indication. The use of a voltmeter in conjunction with a synchroscope will permit accurate angular positioning which minimizes electrical disturbances when the generators are paralleled. Unlike turbine driven or engine driven generators, the generators of synchronous frequency changer sets cannot assume their proper share of load if they are paralleled with an angular displacement between them. They are prevented from doing this by the synchronous driving motors which are already in synchronism and which are rigidly coupled to the generator shafts. Such a condition will only cause the displacement angle to be divided between the two motors and the two generators, with a resulting circulating load between the sets. This can be corrected only by adjustment of the angular displacement by means of the frame shifting device.

The frame shifting device also serves another purpose. It may be seen from Figure 1 that there are several relative angular positions that nearly satisfy the conditions for paralleling both ends of two sets. These occur where there are only a few mechanical degrees of displacement. Such a case exists where poles N4 and S6 of the two motors have the same angular position. By utilizing the frame shifting device on one machine and rotating its stator in the proper direction, the same effect can be achieved as if the rotor of that machine were shifted the few mechanical degrees necessary to correct for its displacement from proper paralleling position. This in effect permits proper paralleling of the two sets in some additional angular relationships, so that a fewer number of poles may have to be slipped when paralleling.

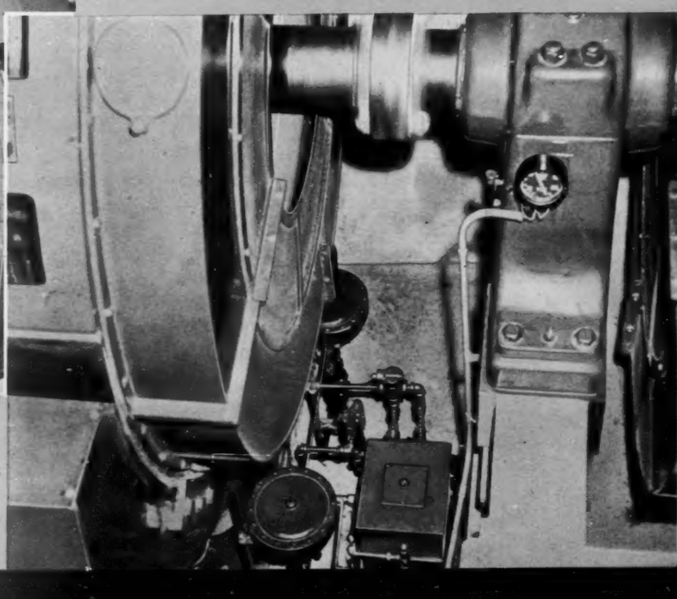
When frame shift is provided it is located on the frame of the higher frequency machine of the set, since this machine has the greater number of poles, and fewer mechanical degrees of shift will be required to accomplish the desired shift in electrical degrees. For 300-rpm sets the shifting device normally provides a 16-degree shift. For 500 or 514-rpm sets a shift of 27 degrees is provided, and for 720 or 750-rpm sets a 38-degree shift is normally provided. The speed of a frequency changer set is, of course, determined by using the highest common speed of the two frequencies, such as 300 rpm for a 60/25-cycle set or 750 rpm for a 50/25-cycle set.

The various possible pole combinations of frequency changer sets can be studied by making pole layouts in duplicate for the particular machines under consideration, similar to the diagrams of Figure 1. The diagram for one set should be made on transparent paper and placed over the other diagram with a pin holding the two together at the axis. Rotation of the transparent diagram will permit observation of the various angular displacements which will be encountered in the paralleling of the sets.



IN COMMON USE, frequency changers such as this 2500-kva, 600-rpm set for converting 60 cycle to 40 cycle power provide off-standard frequencies for special or old installations.

STATOR ANGULAR POSITION of 60 cycle motor is adjusted hydraulically before this set is synchronized with the 40-cycle system.



Analogies in ac Circuit Interruption

by DR. ERWIN SALZER*
Patent Attorney
Boston, Mass.

Applying a brake to a simple pendulum presents an interesting analogy for study of arc interruption.

THERE IS A SIMILARITY in behavior between a mechanical pendulum and an electric circuit. Inertia or mechanical mass, M, and electrical inductance, L, behave in similar manners. The mass, M, tends to maintain a constant velocity, v, and the inductance, L, tends to maintain a constant current, i. The same differential equation relates to the force, f, applied to a mass, M, and the resulting velocity, v, as to the voltage, e, applied to a linear inductance, L, and the resulting current, i $\left(f = M\frac{dv}{dt};\ e = -L\frac{di}{dt} \right)$. The analogy of behavior between the mechanical pendulum and the electric circuit is also predicated upon the similarity between the lifting of a weight by a force, f, and the charging of a condenser by a voltage, e.

In a pendulum, kinetic energy is periodically converted into potential energy and vice versa, while in the case of the ac circuit, magnetic field energy is periodically converted into electric field energy and vice versa. A brake for arresting the oscillations of a mechanical pendulum and an interrupting device for arresting oscillations in an ac circuit are analogous devices insofar as their energy dissipating functions are concerned. Hence a better understanding of the nature of interrupting devices may be reached by a translation of the more familiar concepts relating to mechanical brakes into electrical concepts.

Oscillations in an oscillating system can only be maintained unchanged if energy is supplied to the system from an external energy source at the same rate as energy is being dissipated in the system. Hence to stop oscillation in an oscillating system — either a mechanical pendulum or an ac circuit — the external supply of energy must be cut off to preclude continued feeding of energy from the external energy supply into the system; and both the energy inherent in the system at the time of cut-off, and the energy supplied to the system during the cut-off process, must be dissipated.

A circuit interrupter is a device for cutting off the external supply of energy from an electric circuit and for rapidly dissipating both the energy inherent in the circuit at the time of cut-off and the energy supplied to the system during the cut-off process.

Analogous oscillatory systems

Figure 1 shows, by way of comparison, the oscillations of a mechanical pendulum without friction and the oscillations of an oscillatory electric circuit comprising inductance, L, and capacitance, C, but no ohmic resistance, R. Such a circuit is often briefly referred to as an LC circuit.

At the top level of the figure, six consecutive positions of the pendulum are shown. The next lower or second level of Figure 1 shows, diagrammatically, six consecutive phases of an electric oscillation in an LC circuit. These six consecutive phases correspond to the six consecutive positions of the pendulum shown at the top level of Figure 1.

The values of the voltage, e, and of the current, i, prevailing at the six consecutive phases illustrated at the second level are plotted against time immediately below at the third level. Curve (e) also corresponds to the component of gravitational force (f) driving the pendulum, and curve (L) to the pendulum velocity (v).

The values of the magnetic field energy, W_L, and of the electric field energy, W_C, prevailing in the six consecutive phases shown at the second level of Figure 1 are plotted against time below at the fourth and fifth level.

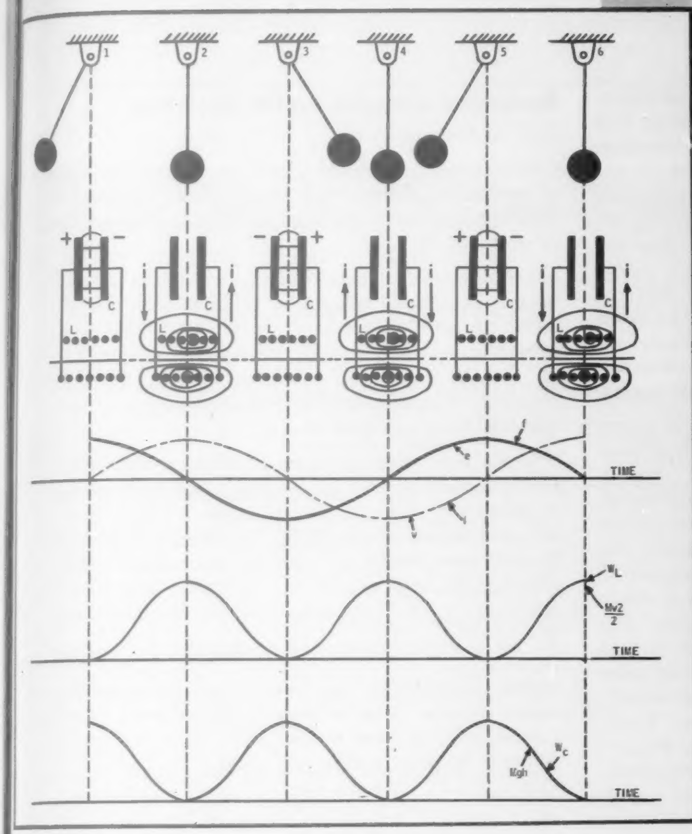
The fourth level also indicates the change of kinetic energy $\frac{1}{2}Mv^2$ with time during the movements of the pendulum shown at the top level. Similarly, the fifth level of Figure 1 also indicates the change of potential energy (Mgh) with time during the movements of the pendulum shown at the top level.

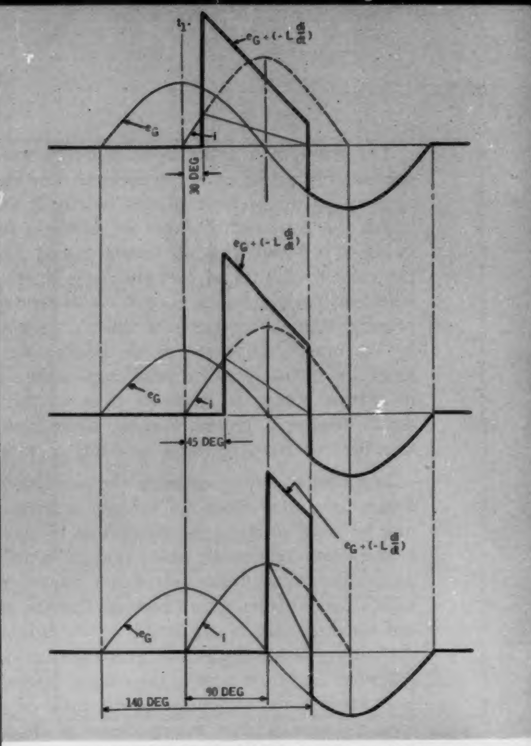
Periodic energy conversion

It is assumed that an initial supply of energy has been stored in both systems; in the pendulum by raising it to a predetermined level and in the electric circuit by charging the capacitance C to the predetermined potential.

The pendulum is accelerated by gravity during its travel from position 1 to position 2, where it reaches its maximum velocity. As the pendulum travels from position 2 to position 3 its velocity decreases as it moves against gravity.

* Dr Salzer was formerly consulting engineer at the Allis-Chalmers Boston Works.





CIRCUIT INTERRUPTION by current limiting fuses is shown in three different cases above. Effects of increased fuse link resistance prior to vaporization have been neglected. **(FIGURE 2)**

ANALOGY between oscillation of a frictionless pendulum and oscillations of an LC circuit are shown. Both involve periodic conversions of energy. **(FIGURE 1)**

In position 1 the kinetic energy of the pendulum is zero and its potential energy maximum. As the pendulum moves toward position 2 its kinetic energy increases and its potential energy decreases. The reverse occurs as it moves from 2 to 3. These periodic conversions by the pendulum of potential energy into kinetic energy and vice versa are shown in the diagrams at the fourth and fifth level of Figure 1.

In the LC circuit shown at the second level of Figure 1 an inductance L (coil) is substituted for the mass of the pendulum and the action of an electric field in a capacitance C (condenser) for the action of the gravitational field. The electric field in capacitance C has been indicated by arrows of which the heads correspond to positive ions and the tails to electrons. The capacitance C is fully charged at 1, and since no current flows at that time the inductance L is not associated with a magnetic field. At 2 the capacitance C is fully discharged and consequently its lines of force representing the electric field have disappeared; yet, though the capacitance C does not act any longer as a source of current, the current continues to flow by reason of the electric inertia of the inductance L. The current flows until the capacitance C is fully recharged at 3, at which time the electric field is opposite to that at the time 1.

During the transition from 1 to 2 all the electric field energy stored in the capacitance C is converted into magnetic field energy. During the subsequent transition from 2 to 3, in turn, all the magnetic field energy stored in the inductance L is converted into electric field energy stored in the capacitance C, etc. These periodic conversions from electric field energy into magnetic field energy and vice versa are clearly shown in the diagrams at levels four and five of Figure 1.

Since Figure 1 refers to a pendulum without friction and to a circuit having no ohmic resistance, no energy will be dissipated and consequently the oscillations will not be damped.

Mechanical brakes vs interrupting devices

In essence, mechanical brakes are predicated upon direct conversion by friction of mechanical energy into heat. Interrupting devices are predicated in essence upon the conversion of electrical energy into heat. The effectiveness of a mechanical brake as well as that of an interrupting device may be expressed in terms of their power dissipating ability. The effectiveness of a mechanical brake to arrest a given mechanical pendulum may be measured by the length of time, or number of cycles, required for completely arresting the oscillations of the pendulum. In a similar way, the interrupting ability of an interrupting device may be measured by the length of time, or number of cycles, required for completely arresting the oscillations of a given electric circuit. We refer to eight, five or three-cycle circuit breakers, depending upon their rated interrupting time in numbers of cycles required for interrupting the ac circuit into which they are connected.

The effect of a brake upon a mechanical pendulum depends very much upon the point of time at which it is applied. If the brake is applied exactly at the instant at which the pendulum changes its direction from an upswing to a downswing, the oscillations of the pendulum can most readily be arrested since the kinetic energy inherent in the pendulum is zero at this instant, thus dispensing with the necessity of dissipating kinetic energy by the brake. However, if an attempt were made to arrest the oscillations of a pendulum at the instant when its kinetic energy is relatively close to maximum, this would require a greater braking effort and conversion into heat of relatively large amounts of kinetic energy.

In a similar way to arresting the oscillations of a pendulum at a time when its velocity is zero, an attempt may be made to arrest the oscillations of an ac circuit at a time when the current passes through a natural current zero. Such synchronization of the interrupting process with a natural current zero requires that the contacts part and reach the critical gap length at which interruption of the current is accomplished. This interruption is within the interval of time close to the natural current zero. This is rather difficult to achieve if the mass of the moving contact system is large, the frequency of the circuit under interruption high (as in the order of 60 cycles per second) and where the circuit comprises multiple phases. Under favorable conditions it may, however, be worth while to aim at synchronizing interruption with a natural current zero, thus minimizing the amount of magnetic energy which must be converted into heat. As a rule, the contacts of circuit interrupters part at random points of time and thus the magnetic field energy of the circuit is likely to be relatively high.

Arresting pendulum and circuit oscillations

Let us assume that the pendulum which we have been considering comprises a rocking pin supported in a suitable bearing, a rod depending from the rocking pin and a weight attached to the end of the rod remote from the pin. We may further assume that a certain amount of energy is dissipated by friction in the bearing of the rocking pin and that this amount of energy is replenished from some appropriate energy source at the same rate as it is being dissipated. Any kind of mechanical brake may be provided to act upon the rocking pin to arrest the oscillations of the pendulum. If the brake is applied relatively gently, the oscillations of the pendulum may be arrested within a few cycles. If the brake is slammed in, the normal oscillations of the pendulum are arrested almost instantly. At a time when its velocity is high, the pendulum weight will have a strong tendency to continue its motion, due to its inherent kinetic energy, and this will result in flexing or elastic deformation of the pendulum arm.

The electrical analogy to slamming in the brake would be the action of an interrupting device which is so effective as to cause almost immediate cessation of current flow. If cessation of current flow is almost immediate, the conversion of magnetic field energy into electrical field energy tends to raise the potential of the circuit and to cause electric stresses in the insulation thereof.

Mechanical analogies explain operation

Current-limiting fuses

Current-limiting fuses and circuit breakers are examples of mechanical systems used for ac circuit interruption. Although both are in the same classification, their methods of operation vary.

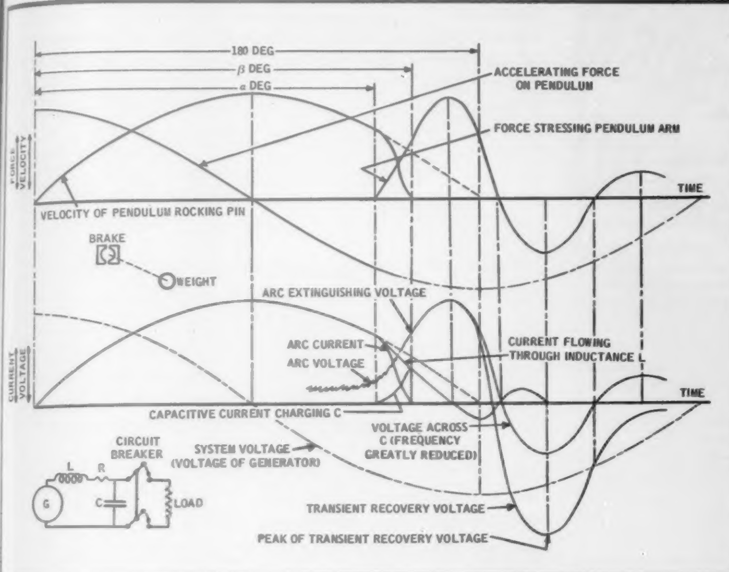
The case where a mechanical system moving at a high velocity is virtually brought to an immediate standstill, making it necessary for large amounts of kinetic energy to find an outlet by way of conversion into some form of potential energy, has its electric counterpart in the operation of current-limiting power fuses, diagrammatically illustrated in Figure 2.

In the three cases shown in this figure a high ac current is reduced to zero in less than a half cycle, making it necessary for large amounts of magnetic energy to find an outlet by way of conversion into electric field energy. To make more evident the phenomenon of inductive surge voltage it has been assumed in drawing Figure 2 that the inductance, L, of the circuit and the rate of current decay, $\frac{di}{dt}$, are so high as to result in inadmissibly high voltage surges. Inadmissibly high surges frequently occurred in current-limiting fuses of early design, but in modern current limiting fuses the inductive surge voltage can generally be kept within safe limits.

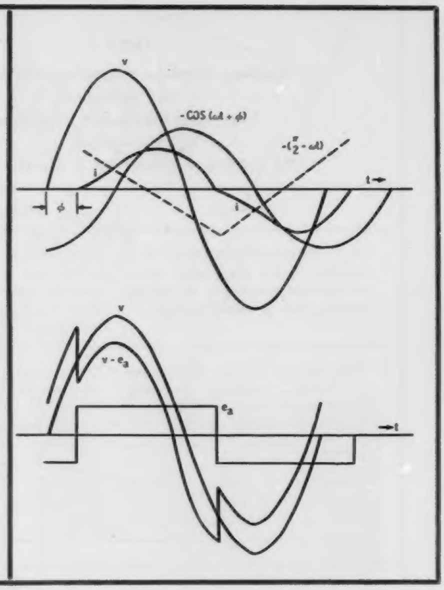
Shown at the top level of Figure 2 is a voltage wave, e_G, and a current, i, lagging the voltage by 90 degrees. The current, i, is allowed to rise normally or sinusoidally up to 30 degrees; and is then caused to decay linearly until it becomes zero at 140 degrees. The inductive voltage $-L\frac{di}{dt}$ generated by changing the current, i, at a high constant rate, $\frac{di}{dt}$, is superposed upon the circuit voltage and causes a voltage surge considerably greater than the peak of the normal circuit voltage. The medium level diagram in Figure 2 shows a current, i, which after a normal or sinusoidal rise of 45 degrees is caused to decay linearly at a higher rate such that it also becomes zero at 140 degrees. Since in this second case the current is relatively higher at the time of initiation of the current-limiting and reducing action than in the case shown at the top level, and since the time within which the current is brought to zero is relatively shorter the rate of change, $\frac{di}{dt}$, and the ensuing inductive voltage are relatively larger. The bottom level diagram of Figure 2 refers to a further step in increase in rate of decay of current flow and the resulting further increase in the inductive voltage in the circuit.

Circuit breaker operation

The interrupting process in a circuit breaker differs from that in a current-limiting fuse inasmuch as the current decay in the former is generally less rapid and occurs nearer to the time of natural current zero. Figure 3 shows, by way of comparison, the process of arresting the oscillations of a physical pendulum by a brake and the



PENDULUM ARRESTED by brake action produces transients similar to those in circuit interruption. Both processes are governed by the same law. **(FIGURE 3)**



SIMPLIFIED arc voltage characteristics. **(FIGURE 4)**

process of interrupting the electrical oscillations of a circuit by a circuit breaker.

To simplify the pendulum diagram at the left top corner of Figure 3 there has been omitted from it the external source of energy required for replenishing the amount of energy dissipated by normal frictional losses in the system. If equilibrium conditions are to be maintained, i.e., if the amplitudes of the pendulum oscillations are to remain unchanged, the amount of energy supplied to the system by the external energy source must be equal to the energy dissipated in the system by frictional losses. An external source of energy suitable for replenishing amounts of energy equal to frictional losses may be constituted by a spring motor acting upon the pendulum by means of some kind of escapement mechanism.

As shown at the top level of Figure 3, the brake begins to act upon the rocking pin of the pendulum after a free travel of α degrees and the rocking pin of the pendulum is completely arrested after a travel of β degrees. The weight of the pendulum overshoots the position corresponding to the final stop position of the rocking pin because of its kinetic energy, resulting in an elastic deformation of the pendulum arm. The pendulum arm and the pendulum weight then vibrate about the final stop position determined by the angle at which the rocking pin had come to a complete standstill. These elastic vibrations occur at the natural frequency of the mechanical system consisting of the pendulum arm and pendulum weight and are of a much higher frequency than that at which the pendulum previously oscillated. The elastic vibrations of the pendulum system are damped considerably so that the pendulum weight comes to rest after a short period of time.

As shown at the lower level of Figure 3 the arc voltage begins to rise more rapidly and the current begins to decay more rapidly than heretofore at α degrees. The current becomes zero at β degrees rather than at 180 degrees which would correspond to the time of natural current zero. The increasing arc voltage causes the capacitance C to be charged by current flowing into it. The arc current and the current charging capacitance C are in parallel. The charging current of capacitance C continues to flow after the arc current has become zero at β degrees and causes a rise of the voltage across the arc gap of the circuit interrupter above the arc-extinguishing voltage. The magnitude of this voltage peak depends upon the capacitance C and upon the time interval between actual current zero and natural current zero.

Upon arc extinction the magnetic field energy stored in the inductance L of the circuit is converted into electric field energy and the latter is reconverted into magnetic field energy, etc. These periodic conversions of energy are due to the fact that the capacitance C and the inductance L form an oscillatory circuit which oscillates at its natural frequency after the arc current has become zero. The voltage accompanying the periodic discharges and recharges of capacitance C is superimposed upon the voltage of the generator and the resulting voltage appearing across the separated contacts of the circuit interrupter is known as the transient recovery voltage.

Mechanical friction and arc voltage

Qualitatively there is a perfect analogy between the force acting on the brake of our pendulum and the arc voltage in a circuit interrupter counteracting the flow of current through the interrupter.

TABLE I

Analogy between Pendulum and Circuit and between Stopping a Pendulum by a Brake and Interrupting a Circuit by a Circuit Breaker

	Pendulum	Electric System
I	The mechanical oscillations of a pendulum are predicated upon a periodic conversion of kinetic energy and potential energy.	The electrical oscillations of a circuit are predicated upon a periodic conversion of magnetic field energy and potential field energy.
II	The periodic energy conversions of a simple pendulum involving no frictional losses are governed by the reversible equation $M \cdot g \cdot h \cdot \rightleftarrows \frac{1}{2} M \cdot v^2$ wherein M = mass, g = acceleration due to gavity, h = distance of lift and v = velocity.	The periodic energy conversions of a circuit involving no electric losses are governed by the reversible equation $\frac{1}{2} Li^2 \rightleftarrows \frac{1}{2} Ce^2$ wherein L = the inductance, i = current, C = capacitance, and e = voltage.
III	Where there are frictional losses in a pendulum system these losses may be replenished by a driving spring motor whereby the oscillations of the system may be maintained unchanged.	Where there are electric losses in a circuit these losses may be replenished by a generator whereby the oscillations of the circuit may be maintained unchanged.
IV	Considering a physical pendulum driven by a spring motor and having a flexible pendulum arm for supporting the pendulum weight, we may distinguish between two frequencies: (1) The frequency f_o at which the pendulum oscillates during steady state conditions under the action of the driving spring motor. (2) The natural frequency f_n of the elastic vibrations of the pendulum-arm-pendulum-weight system which is a matter of the mechanical constants thereof.	Considering a circuit energized by a generator and having both inductance and capacitance, we may distinguish between two frequencies: (1) The frequency f_o at which the circuit oscillates during steady state conditions when energized by the generator. (2) The natural frequency of f_n of the electric oscillations of the circuit which is a matter of the electrical constants thereof.
V	In terms of energy the frictional losses in the bearing of a physical pendulum are a conversion of mechanical energy into heat.	In terms of energy the $I^2 \cdot R$ losses due to loads in a circuit are a conversion of electric energy into heat.
VI	Greatly increased friction resulting from application of the brake causes a transient condition and ultimate cessation of the pendulum (which occur at the frequency f_o imposed by the driving spring motor).	Greatly increased resistance resulting from addition of arc resistance to the resistance of the circuit causes a transient condition and ultimate cessation of the oscillations of the circuit (which occur at the frequency f_o imposed by the generator).
VII	When the brake is rapidly applied to the pendulum-arm-pendulum-weight system, the kinetic energy inherent therein at the time causes damped transient elastic vibrations of the pendulum-arm-pendulum-weight system occurring at the latter's natural frequency f_n.	When the breaker is rapidly operated to interrupt the circuit, the magnetic energy inherent therein at the time causes damped transient oscillations of the circuit occurring at the latter's natural frequency f_n.

Quantitatively there is a perfect analogy between so-called viscous damping of the motion of a mechanical system which involved frictional forces linearly proportional to velocity and the effect of an ohmic resistance inserted into a circuit. Viscous damping is governed by the equation

$$f = D \cdot v \tag{1}$$

where f = braking force

D = damping constant

v = velocity

The effect of an ohmic resistance placed into a circuit is expressed by Ohm's law

$$e = R \cdot i$$

The interruption of a circuit by progressive insertion of an ohmic or linear resistance is a process wholly governed by Ohm's law; but the interruption of a circuit by progressive insertion of arc resistance is a process that does not follow Ohm's law; since arc drop, arc resistance and arc current are not related by Ohm's law. A mathematical model brake wherein braking force, damping constant and velocity are related in the same way as arc drop, arc resistance and arc current would be a complete mechanical analogy to a circuit interrupter. The quantitative analogy between mechanical brake and circuit interrupter ends when we consider a real brake rather than such a mathematical model brake. This, however, does not impair the usefulness of a comparative analysis of the two oscillation arresting processes. It merely puts a limit to the analogy beyond which nonanalogous lines of thought must be followed in investigating circuit interruption.

Simplified and actual voltage characteristic

A simplified mathematical model of the arc voltage characteristic obtained by neglecting the reignition and extinction peaks would consist of a series of rectangles e_a, as shown in the lower portion of Figure 4. This figure also shows a sinusoidal voltage v applied to an inductive circuit which includes the arc gap across which arc voltage e_a prevails, and also the resulting voltage $v - e_a$ across the inductance L of the circuit. The upper portion of Figure 4 shows the current, i, which lags the applied voltage by ϕ degrees. The current, i, can be conceived as consisting of two components, one varying sinusoidally with time and the other increasing and decreasing linearly with time, resulting from the rectangular arc voltage. It is apparent from Figure 4 that the current, i, in a circuit to which a sinusoidal voltage is applied is not sinusoidal if the circuit includes an arc gap.

When investigating actual cases of ac circuit interruption, the arc voltage developed in any particular piece of apparatus must be substituted for the flat top arc voltage which has been considered above. Arc voltage is a very real concept and a very tangible quantity since it can readily be seen and measured in any appropriate oscillogram of an interruption. It is frequently helpful to think of the arc voltage as a braking force which brings the flow of current to a standstill at a point of time which permits the subsequent increase of the dielectric strength of the arc gap to permanently exceed the recovery voltage of the circuit.

s

ns

e

A-C

CHALMERS

RANS-
breaker
ace the
simply